Acoustic Monitoring of Flow Through the Strait of Gibraltar: Data Analysis and Interpretation

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LONG-TERM GOALS

Existing techniques do not begin to exploit the full potential of acoustic remote sensing methods to study ocean thermal structure and circulation. This research is intended to improve our understanding of acoustic propagation in shallow-to-intermediate depth environments and to extend tomographic techniques to ocean regimes in which acoustic propagation is more complex than the largely deep-water cases studied to date.

OBJECTIVES

Understanding the acoustic forward problem in complicated environments is a prerequisite to using tomographic methods. The conditions in the Strait of Gibraltar include substantial variability on short time and space scales, including internal bores and trains of interfacial internal waves. The specific issues addressed in this project are: (i) to determine whether one or more acoustic ray paths exist (at 2 kHz) that are resolvable, identifiable, stable, and that provide useful integral measures of the flow; (ii) to measure acoustic scattering due to the internal wave bores in the Strait; and (iii) to study normal mode propagation (at 250 Hz), including the feasibility of using modal analyses, matched field tomography, and full-field inversion techniques to obtain information on the temperature and current fields. At the conclusion of the analyses we expect to have a much better understanding of acoustic propagation in the complex oceanographic environment present in the Strait of Gibraltar and, by extension, in other straits that are two-layer systems. We also expect to have determined which of the various possible acoustic methods for monitoring the transport in the Strait works best, and just how well the various methods tried do work.

APPROACH

We are focusing on the use of differential travel times (at 2 kHz), horizontal ray arrival angles (at 2 kHz), and normal mode group delays and amplitudes (at 250 Hz) as the observables to use in the inverse problem for ocean sound speed and current, using data from a short-term feasibility test conducted during April-May 1996. Extensive independent measurements of the temperature, salinity, and velocity fields in the Strait were made. Satellite synthetic aperture radar (SAR) images of the Strait were acquired to provide information on the evolution of the internal wave bores. Three current

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meter moorings provided data spanning the Strait near its eastern end. We are doing extensive forward modeling of the acoustic propagation in the Strait, using a variety of propagation codes, a synthesis of the sound speed and current meter data, and models for the internal wave bore structure as a function of space and time. Good matches will both help to explain the acoustic observations and allow us to extract more information from inverse methods.

WORK COMPLETED

Analysis efforts to date have focused on (i) understanding the effects of the internal wave bores in the Strait on acoustic propagation and (ii) assessing the precision with which acoustic measurements can measure the transports of mass and heat through the Strait.

C. Tiemann, a graduate student supported by an AASERT grant and working under the supervision of Worcester and Cornuelle, has played the leading role in the analyses for internal bore effects (Tiemann et al., 1999a,b). Our efforts have involved four different elements: (i) processing of the acoustic data to extract common features observed in the travel times during passage of the bore; (ii) construction of models of the background sound-speed field using the environmental data obtained during the experiment; (iii) construction of models of the bore structure in space and time using a variety of historical information; and (iv) ray tracing through the modeled sound speed fields for comparison with the measured acoustic travel times. The observed arrival pattern has proved to be quite sensitive to the structure of the interface between the inflowing Atlantic water and outflowing Mediterranean water, both in the mean and during the passage of the bore. Tiemann has begun preparation of a manuscript summarizing his research.

Efforts to assess the precision with which acoustic methods can measure the transports of mass and heart through the Strait have been in progress for some time (Worcester et al., 1997, 1999). Sum and difference travel times have been computed, and estimates made of the range and depth averaged sound speed perturbations and current components parallel to the acoustic paths. The phase differences between two horizontally separated receivers were also computed to assess the feasibility of using horizontal arrival angle fluctuations to measure the integrated current perpendicular to the path. A preliminary attempt to use scintillation techniques to measure the current perpendicular to the path has also been made. During FY99 inverse methods were applied to make a quantitative assessment of the precision with which acoustic methods provide estimates of the lower-layer mass transport in the Strait (Send *et al.*, 1999). A manuscript describing these results is nearly complete and will be submitted in the near future.

RESULTS

Internal wave bore effects. The acoustic data from high frequency (2-kHz) reciprocal transmissions across the Strait are unique in that they clearly isolate the acoustic effects of passing internal bores without the added complexity of surface and bottom interactions. These bores have amplitudes as high as 100 m peak to peak and wavelengths of 1 km. They are found at the interface depth and travel with a phase speed of 1-2 m/s. The bores eventually disintegrate into trains of internal solitary waves. The transmissions through the strong tidal flows, internal bores, and trains of interfacial internal waves have complex travel time fluctuations and path structure. The data show that the earliest acoustic arrival, from a deep-going ray which samples only the lower Mediterranean water layer, was stable over the duration of the experiment and has a strong tidal signal. The later arrivals are from shallow rays that sample the interface between the two water layers. They also show tidal variability, but the path structure is more complicated, with the shallow rays smeared into a broad cluster of arrivals that are difficult to track. Although the acoustic scattering caused by each internal bore is different, some common characteristics can be identified. The travel time of the earliest ray decreases with each passing of the bore, followed by a sudden increase in travel time shortly after the bore has passed. Differential travel times from reciprocal transmissions show such travel time changes to be an effect of temperature, rather than current. Warm shallow water is probably being displaced deeper by the bore to the depths of the instruments, increasing the sound speed near the endpoints of the deep-going rays. Both the shallow and deep ray arrivals show much more scattering in the hours following a bore crossing, with some shallow rays arriving at the same time as the deep rays. This effect suggests that the interface layer is deepened behind the passing bore and is slow in restoring itself, so that shallow rays travel through warmer water for an extended time period.

Acoustic propagation models through range- and time-dependent sound speed fields representing the Strait of Gibraltar and perturbed by internal bore models are being used to understand these observations. We are now able to reproduce the overall behavior of the travel time fluctuations caused by the passage of the internal wave trains resulting from the bores (Tiemann, 1999a,b). Somewhat surprisingly, predictions that reproduce the observed features seem to require a background sound-speed profile with multiple near-surface sound-speed minima. The background sound-speed field at the time of the measurements is not well known, in spite of extensive conventional measurements, but many of the measured profiles do contain double minima of the type required. We are proceeding to investigate to what aspects of the bore the acoustics are most sensitive. The next step will be to study the inverse problem, to determine whether acoustic data can be used to observe important properties of the bores, such as the direction of propagation and phase speed.

Transports of mass and heat. Reciprocal acoustic transmissions provide the most promising approach to measuring current in the lower layer (Mediterranean outflow) of the various possible methods that were tested. The accuracy of the lower-layer current measurements using reciprocal acoustic transmissions across the Strait has now been estimated using inverse methods (Send *et al.*, 1999). The flow acoustically averaged along the ray path across the Strait was correlated with the estimate of the same quantity from direct flow observations at 94% (variance explanation). Using estimates of the horizontal and vertical covariance scales for the tidal and low-frequency flows made from direct measurements, the uncertainty for the lower-layer transport is 0.3 Sv (out of ±5 Sv) for the tidal transport and 0.1–0.2 Sv (out of 0.8 Sv mean) for the low-frequency transports.

IMPACT/APPLICATIONS

This research has the potential to affect the design of acoustic systems that must function in complex two-layer environments such as the Strait of Gibraltar, whether for acoustic remote sensing of the ocean interior or for other applications. Internal wave bores, in particular, appear to be more ubiquitous in shallow water than previously realized, making a full understanding of their impact on acoustic propagation crucial to predict the performance of acoustic systems.

Monitoring the variability of the transport through the Strait of Gibraltar is important for a wide range of oceanographic problems. Acoustic methods have the potential to directly provide spatially-averaged measures of the flow, and are therefore strong candidates for providing routine, rapidly repeated, transport measurements. If this research is successful, it could lead to the application of acoustic methods for long-term monitoring of transport in the Strait of Gibraltar and, by extension, in other similar straits.

TRANSITIONS

None.

RELATED PROJECTS

A preliminary equipment test in Knight Inlet was part of a much larger Knight Inlet Experiment led by D. Farmer (IOS, Canada). The Strait of Gibraltar experiment is a joint effort with U. Send (University of Kiel, Germany). In addition, we are collaborating with J. Apel (Global Ocean Associates), who is analyzing the SAR images.

PUBLICATIONS

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